H1 measurements of deeply virtual Compton scattering and studies of vector meson production

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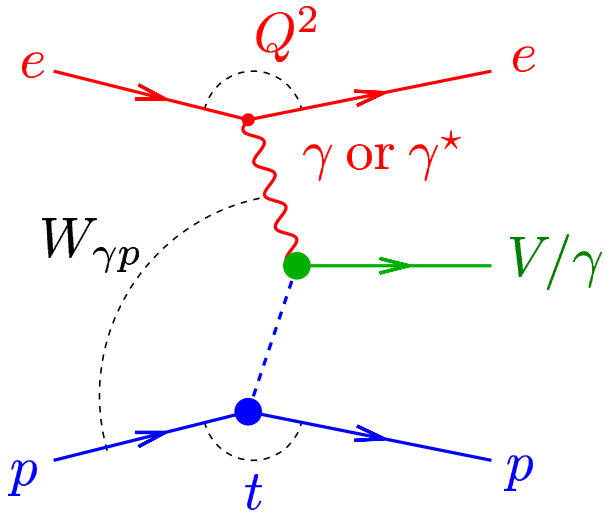
On behalf of the
H1 Collaboration

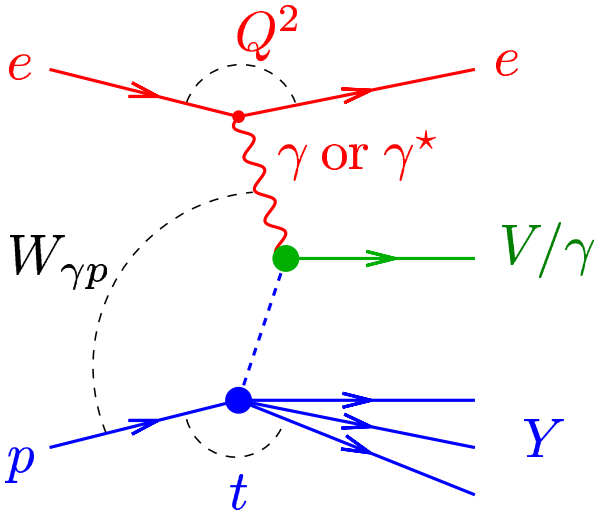
Workshop on Low x Physics

Sinaia, Romania ● 29th June - 2nd July 2005

Elastic



Dissociative



Proton dissociation dominates at large $|t|$

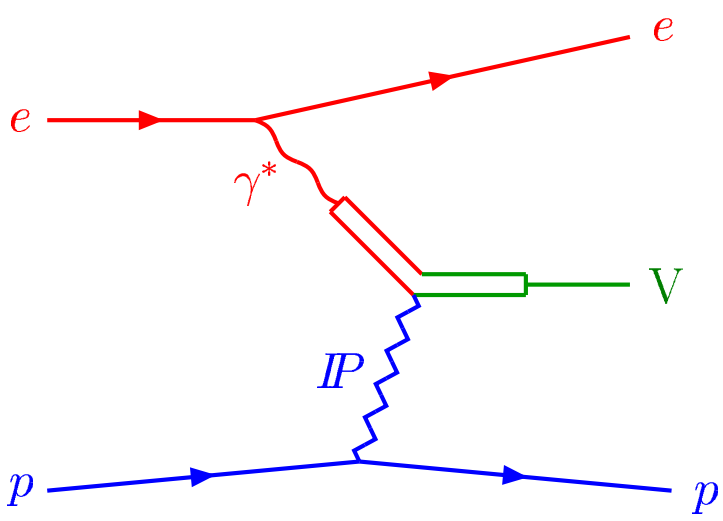
Q^2	Virtuality of the $\gamma^\star$	$\sim 0 < Q^2 < 100\ \mathrm{GeV}^2$
$W_{\gamma p}$	CM energy of the γp system	$20 < W_{\gamma p} < 305\ \mathrm{GeV}$
t	(4 momentum transfer at the p vertex)^2	$\sim 0 < \lvert t \rvert < 30\ \mathrm{GeV}^2$
V	Vector meson	$\rho^0, \omega, \phi, J/\psi, \psi(2s), \Upsilon(1s)$

$\Rightarrow$ Simultaneous probe of several different kinematical quantities

Theoretical Models of Exclusive Vector Meson Production

Regge Theory:

- Soft pomeron exchange



- Slow rise of cross section with W

$$\sigma \propto \left(\frac{W}{W_0}\right)^{4\alpha_{I\!P}(t)-1} \approx W^{0.22}$$

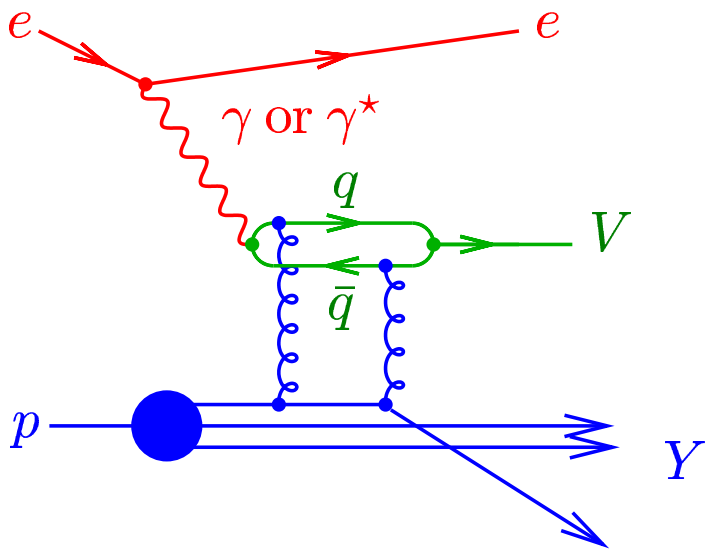
- Shrinkage $\Rightarrow$ t slope varies with W

$$\frac{d\sigma}{dt} \propto e^{-bt} : \; b = b_0 + 4\alpha'(I\!P)\ln\left(\frac{W}{W_0}\right)$$

- Works for light VMs at $Q^2 \approx 0$ and $t \approx 0$

pQCD Models:

- Exchange of ≥ 2 gluons



- Steeper rise in cross section due to g

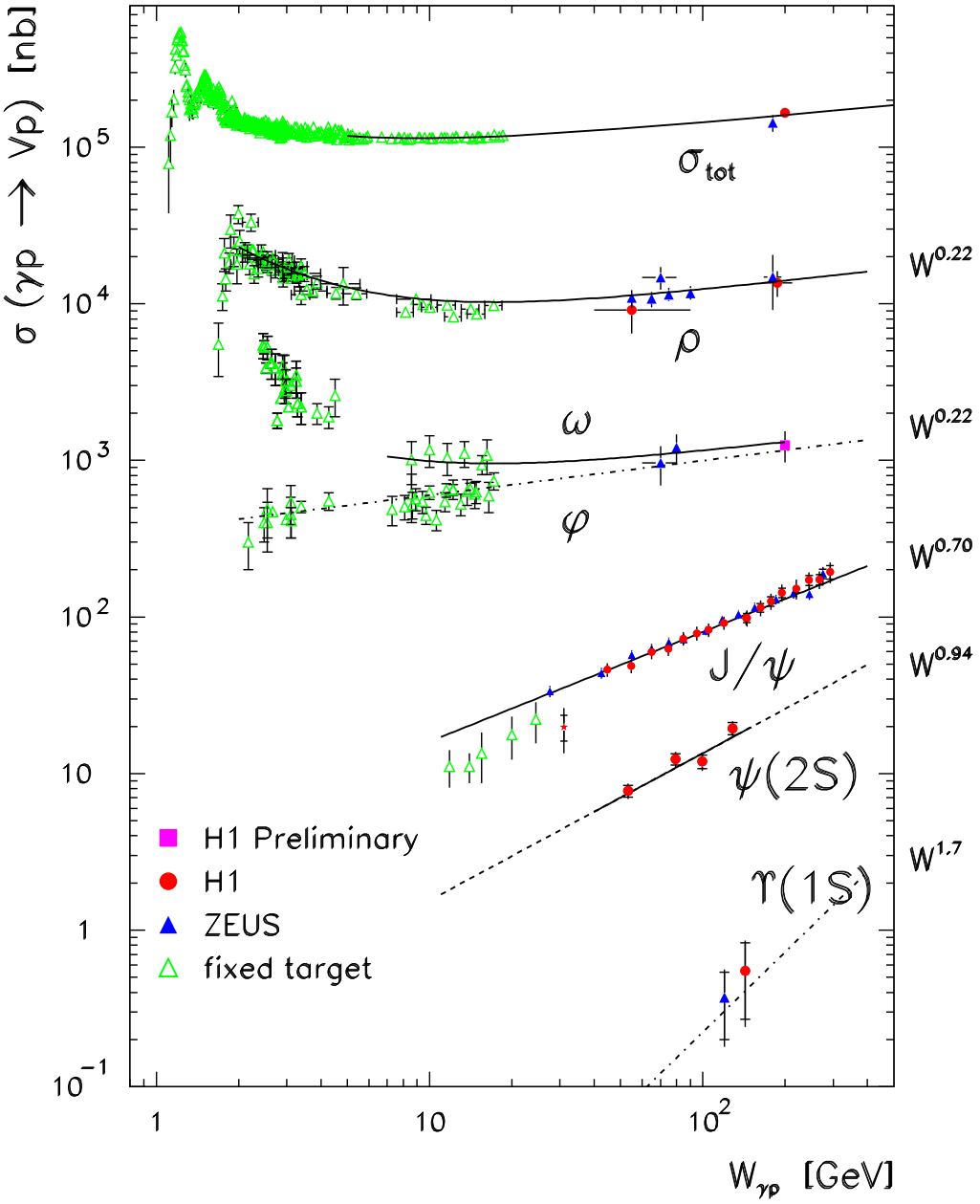
$$\sigma \propto [xg\left(x, Q^2\right)]^2 \text{ naively}$$

- Power law dependence at large $|t|$

$$\frac{d\sigma}{dt} \propto |t|^{-n}$$

- Calculations require hard scale: M_V^2, Q^2, t

Elastic Vector Mesons in Photoproduction



- Total photoproduction cross section for elastic VM production (small $|t|$ & Q^2)

Light Vector Mesons (ρ, ω, ϕ):

- Observed dependence is $\sigma \sim W^{0.22}$

  $\Rightarrow$ Consistent with soft $I\!P$ expectation

Heavier Vector Mesons $(J/\psi, \psi(2s))$:

- Steeper rise in cross section observed

  $\Rightarrow$ Need something in addition to soft $I\!P$

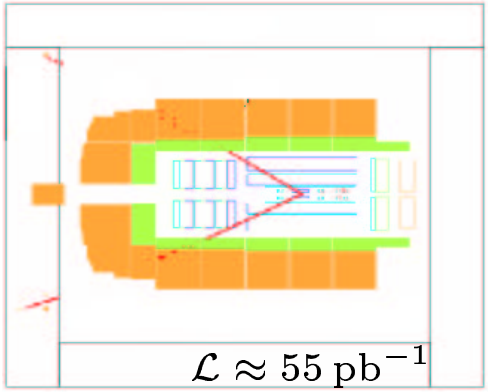
- See break down of pomeron universality

  $\Rightarrow$ VMs at HERA provide a test of the transition between soft & hard regimes

Elastic J/Ψ

$J/\psi \to \mu^+\mu^-/e^+e^-$ in 99/00 data with $t < 1.2\,\mathrm{GeV}^2$ & $Q^2 < 1\,(80)\,\mathrm{GeV}^2$ for $\gamma p\,(ep)$

- Selected by 2 oppositely charged leptons (+scat. e) in 3 topologies:-



Track-Track (TT): Two tracks with at least one muon in $ep/\gamma p$

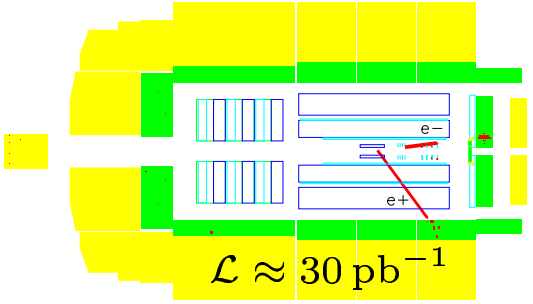
- Two tracks with $P_t > 0.8\,\mathrm{GeV}$ within CJC/CMD $(20 < \theta < 160^\circ)$
- $ep \Rightarrow$ scattered e with $E > 12\,\mathrm{GeV}$ in SpaCal $(160 < \theta < 177^\circ)$

  $\Rightarrow 40 < W < 160\,\mathrm{GeV}^2$

Track-Cluster (TC): One track & one cluster electron in γp

- Track with $P\,(P_t) > 0.8\,(0.7)\,\mathrm{GeV}$ within CJC $(80 < \theta < 155^\circ)$
- Cluster with $E > 4.2\,\mathrm{GeV}$ detected in SpaCal $(160 < \theta < 177^\circ)$

  $\Rightarrow 135 < W < 235\,\mathrm{GeV}^2$

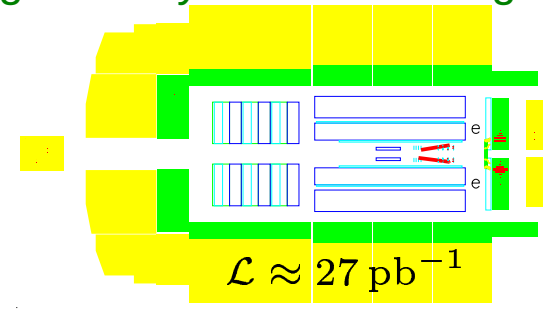


Significantly extend W range

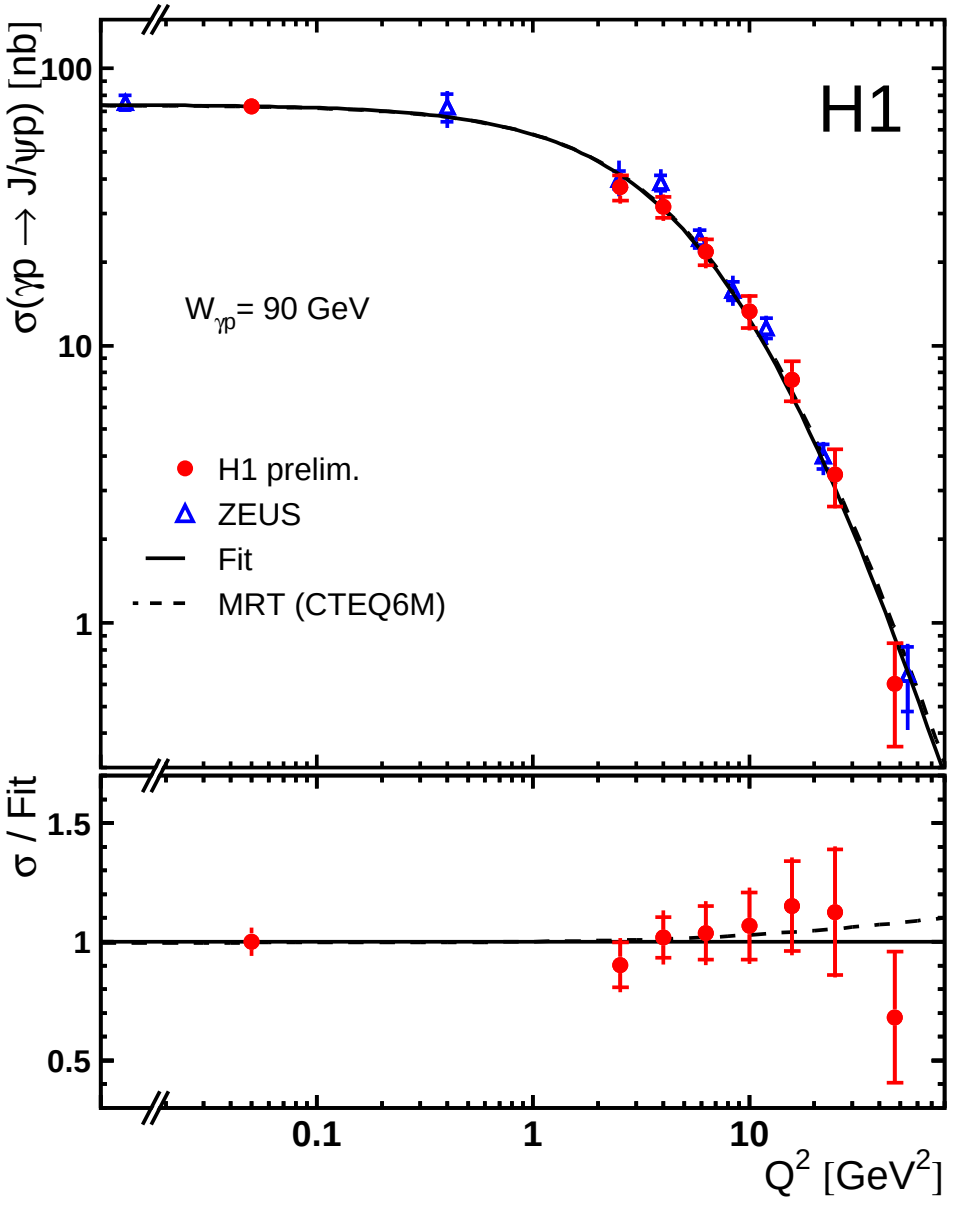
Cluster-Cluster (CC): Two cluster electrons in γp

- Two clusters with $E > 4.2\,\mathrm{GeV}$ & $E > 6.0\,\mathrm{GeV}$ found in SpaCal with $160 < \theta_1 < 174^\circ$ & $160 < \theta_2 < 175.5^\circ$ (1 validated by BST)

  $\Rightarrow 205 < W < 305\,\mathrm{GeV}^2$



Elastic J/Ψ: Q^2 Dependence



- Well fitted by form $\sigma \propto \left(Q^2 + M_V^2\right)^{-n}$
  $\Rightarrow n = 2.486 \pm 0.080 \pm 0.068$

- Slight down-shift of data compared to old H1 results but consistent within errors

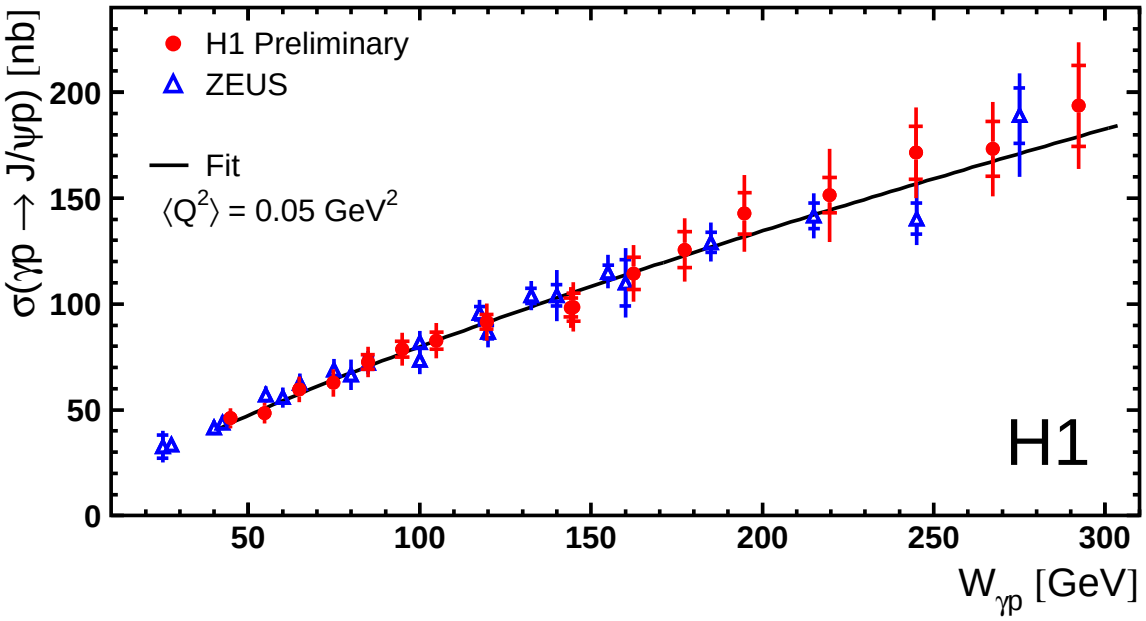
MRT pQCD Model:

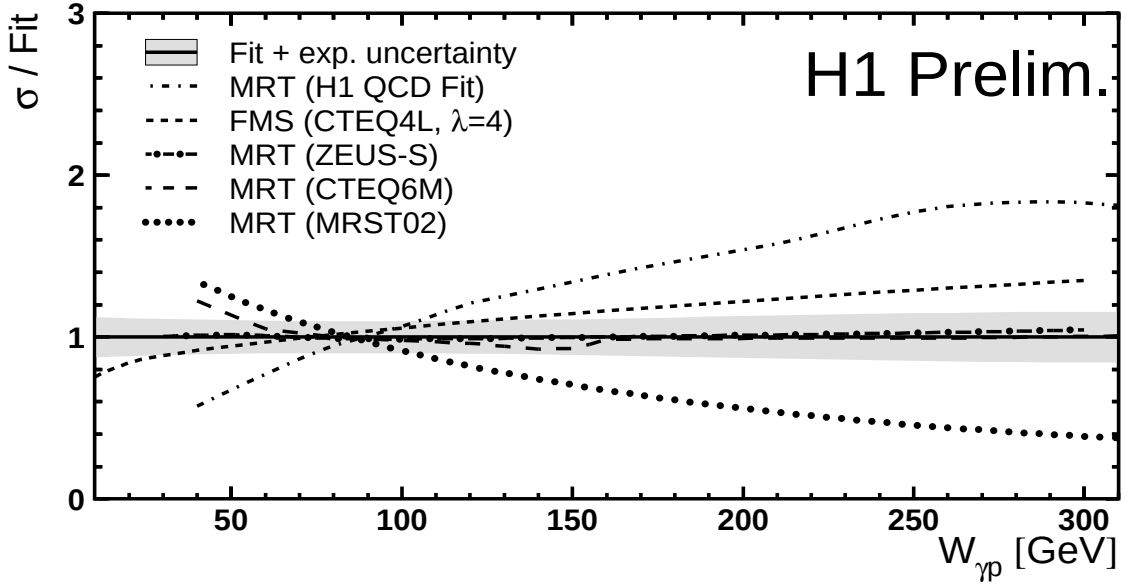
- K_T factorisation + parton-hadron duality
  $\Rightarrow$ open $c\bar{c}$ production with projection of $J^P = 1^-$ state in appropriate mass interval

- Includes effect of skewed gluon distribution
  $\Rightarrow$ enhances cross section mainly at high Q^2

- Provides a good description of the data when normalised to photoproduction point

Elastic J/Ψ: W Dependence





- Excellent agreement with both the ZEUS and previous H1 results
- Fit with power law $\sigma \propto W^{\delta}$:

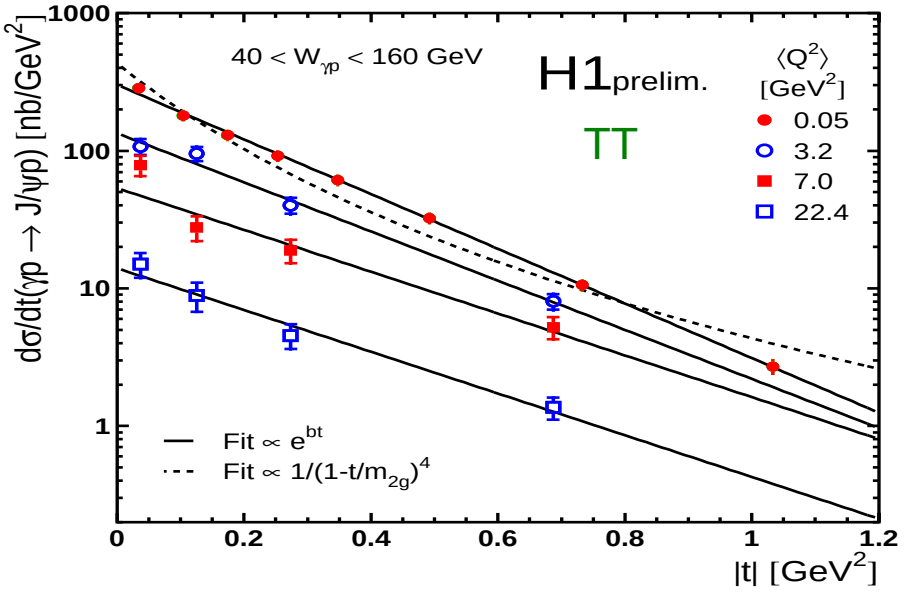
  Photoproduction $(\langle Q^2 \rangle = 0.05\,\mathrm{GeV}^2)$

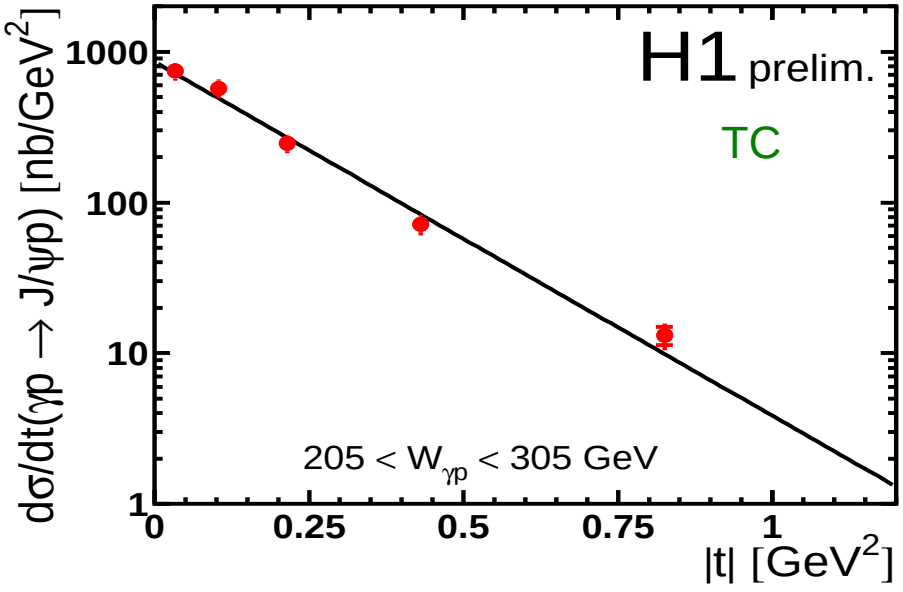
  $\Rightarrow \delta = 0.740 \pm 0.034 \pm 0.034$

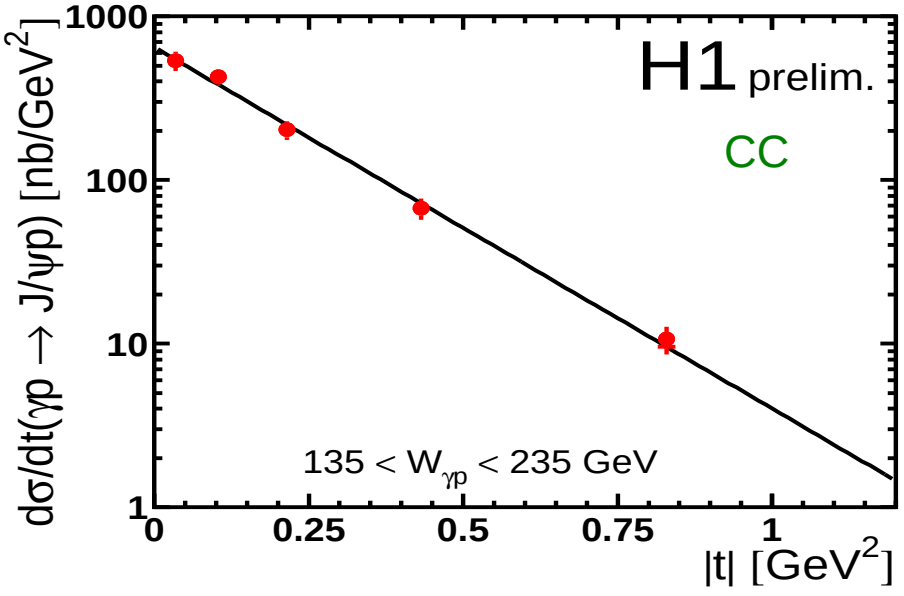
  Electroproduction $(\langle Q^2 \rangle = 3.2\,\mathrm{GeV}^2)$

  $\Rightarrow \delta = 0.67 \pm 0.20 \pm 0.14$
- No observed dependence of power δ on Q^2 within errors (J/ψ mass already provides hard scale)
- Data may be able to constrain gluon PDFs at low x (least well described)

Elastic J/Ψ: t Dependence







- Data well described by simple exponential

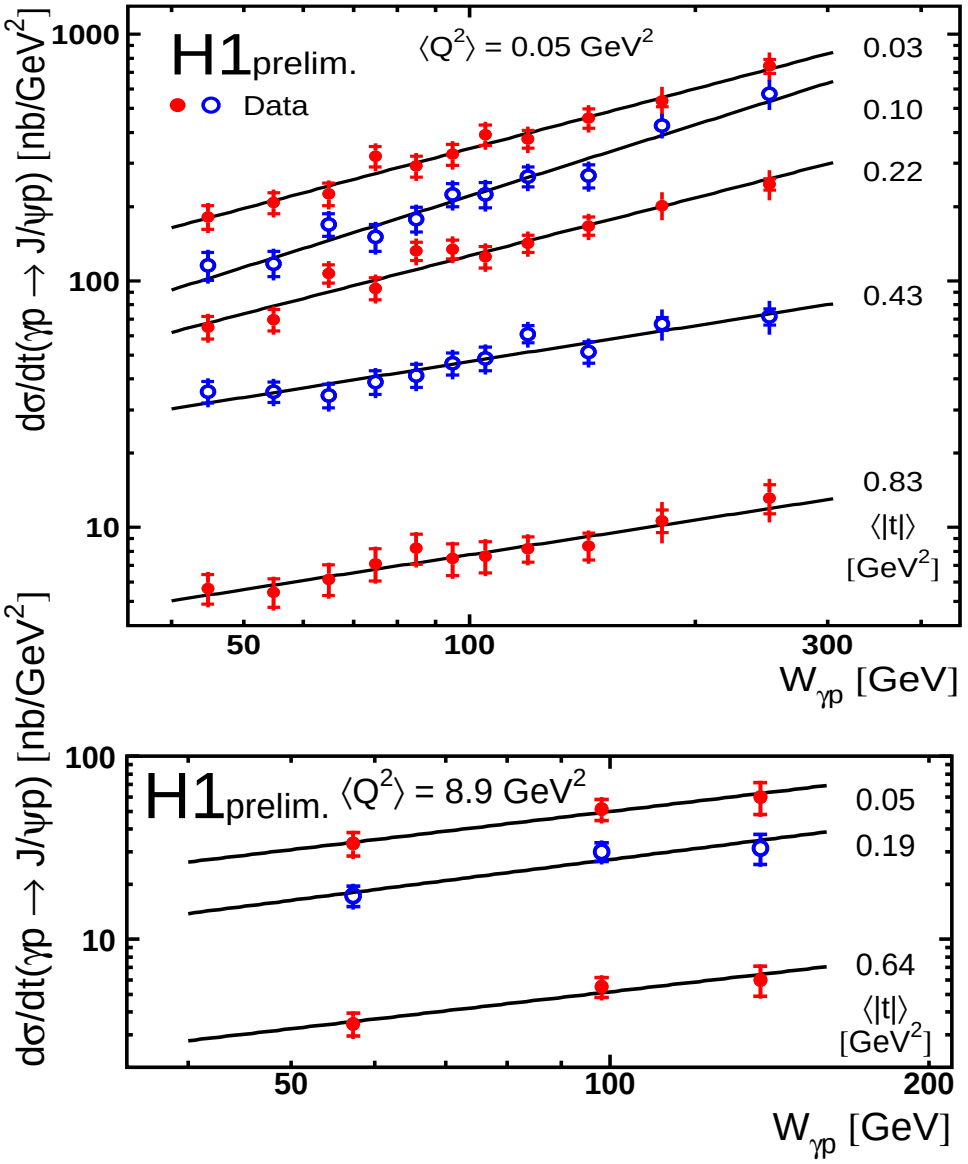
$$\frac{d\sigma}{dt} \propto e^{-bt} \qquad \Rightarrow \chi^2 = 0.25$$

- No significant variation of slope b with Q^2

- Dipole formalism (FMS) clearly disfavoured

$$\frac{d\sigma}{dt} \propto \frac{1}{\left(1-t/m_{2g}\right)^4} \qquad \Rightarrow \chi^2 = 5.5$$

Elastic J/Ψ: W - t Dependence



- Data well described by 1 dimensional fit

$$\frac{d\sigma}{dt}(W, \langle t \rangle) \propto W^{4\alpha(\langle t \rangle)-1}$$

- A two dimensional fit of the form

$$\frac{d\sigma}{dt}(W, t) \propto e^{-b_0 t} W^{4\alpha(t)-1}$$

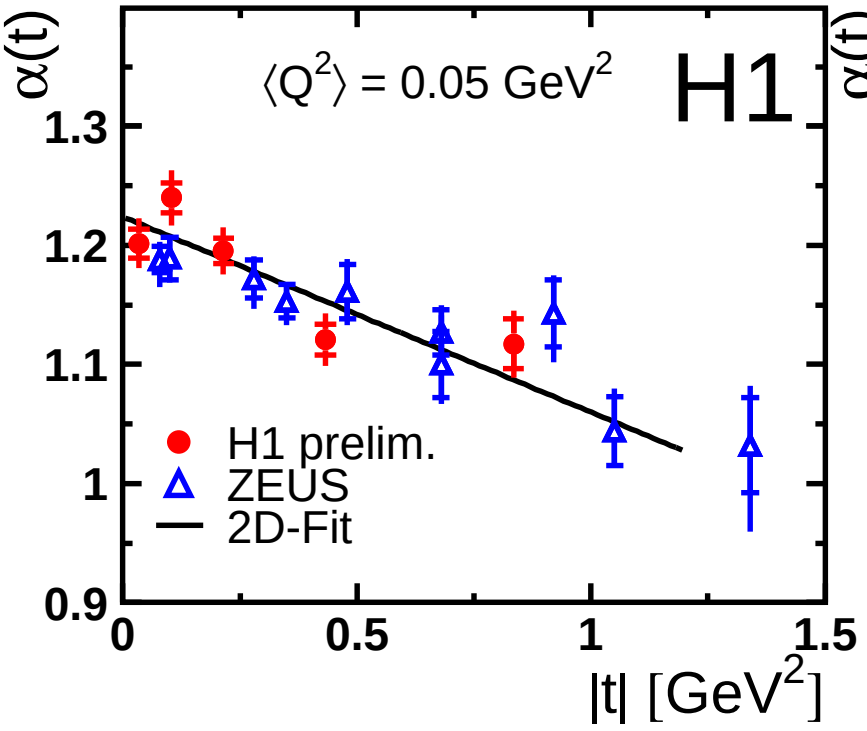
allows access to effective $I\!P$ trajectory

$$\alpha(t) = \alpha_0 + \alpha' t$$

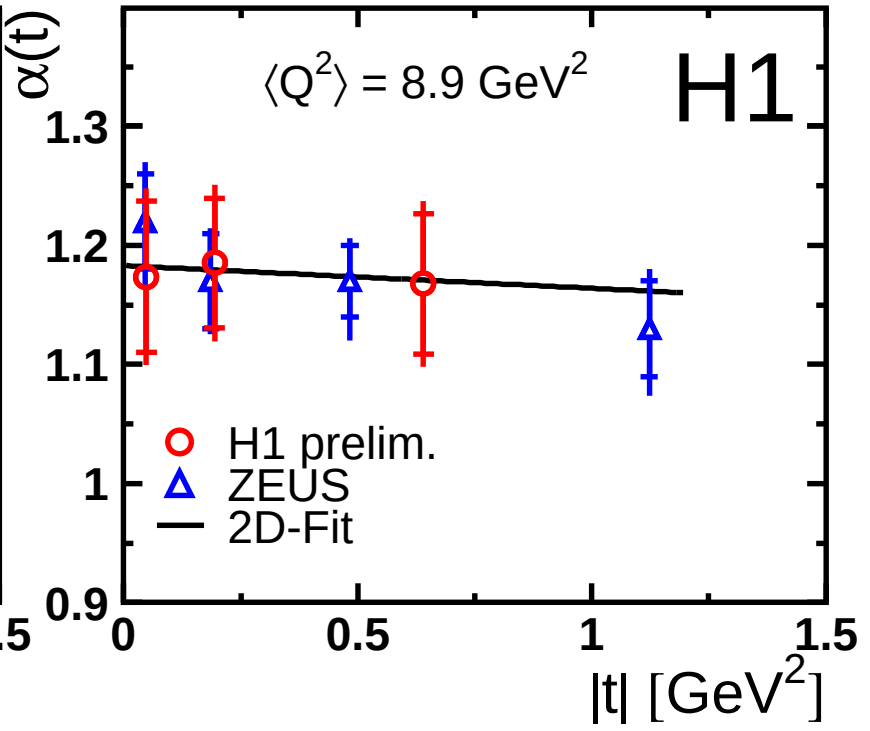
- Fit extracts α_0, α', b_0 (and normalisation parameters for the 3 separate samples) ...

Elastic J/Ψ: Effective Pomeron Trajectory

Photoproduction:



Electroproduction:



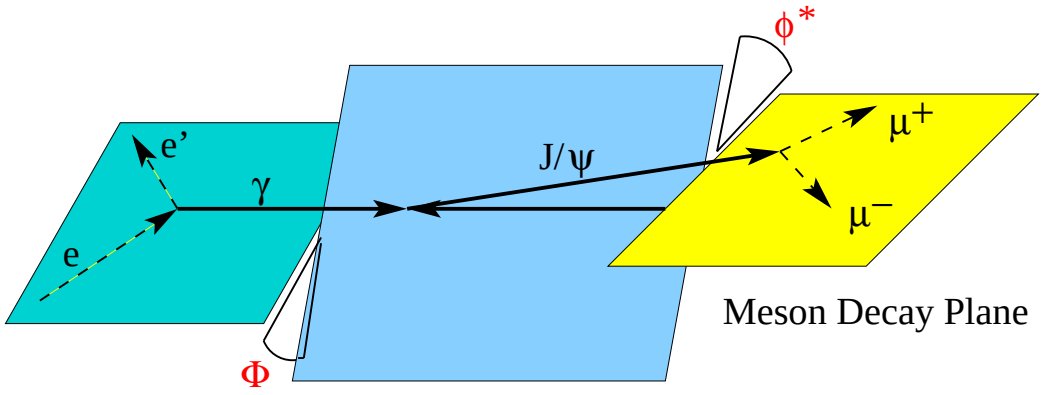
- $\alpha_0 = 1.224 \pm 0.010 \pm 0.012$
- $\alpha' = 0.164 \pm 0.028 \pm 0.030\,\mathrm{GeV}^{-2}$

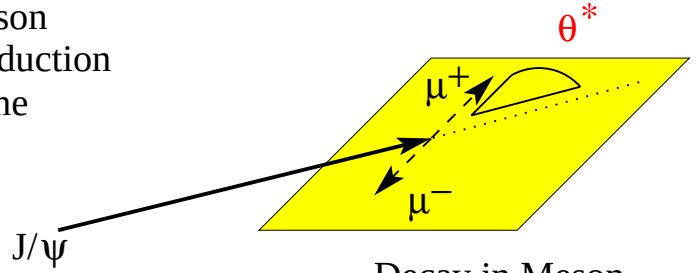
- $\alpha_0 = 1.183 \pm 0.054 \pm 0.030$
- $\alpha' = 0.019 \pm 0.139 \pm 0.076\,\mathrm{GeV}^{-2}$

$\Rightarrow$ Trajectories are compatible within uncertainties

- Intercept larger $(\alpha_{IP}(0) \approx 1.08)$ and slope shallower $(\alpha' \approx 0.25\,\mathrm{GeV}^{-2})$ than Regge prediction
- Shrinkage $(b(W))$ is observed in photoproduction (but is inconclusive for electroproduction)

Spin Density Matrix Elements (SDMEs)





$$\Psi = \phi^* - \Phi$$

$$\frac{d\sigma}{d\cos\theta^*} \propto 1 + r^{04}_{00} + \left(1 - r^{04}_{00}\right)\cos^2\theta^*$$

$$\frac{d\sigma}{d\phi^*} \propto 1 + r^{04}_{1-1}\cos 2\phi^*$$

$$\frac{d\sigma}{d\Psi} \propto 1 - \epsilon r^{1}_{1-1}\cos 2\Psi$$

$$\frac{d\sigma}{d\Phi} \propto 1 - \epsilon\left(r^{1}_{00} + 2r^{1}_{11}\right)\cos 2\Phi + \sqrt{2\epsilon\left(1+\epsilon\right)}\left(r^{5}_{00} + 2r^{5}_{11}\right)\cos\Phi$$

- Production & decay angular distributions

  $\Rightarrow$ 15 spin density matrix elements

  but only 3 accessible in photoproduction

- SDMEs depend on helicity amplitudes

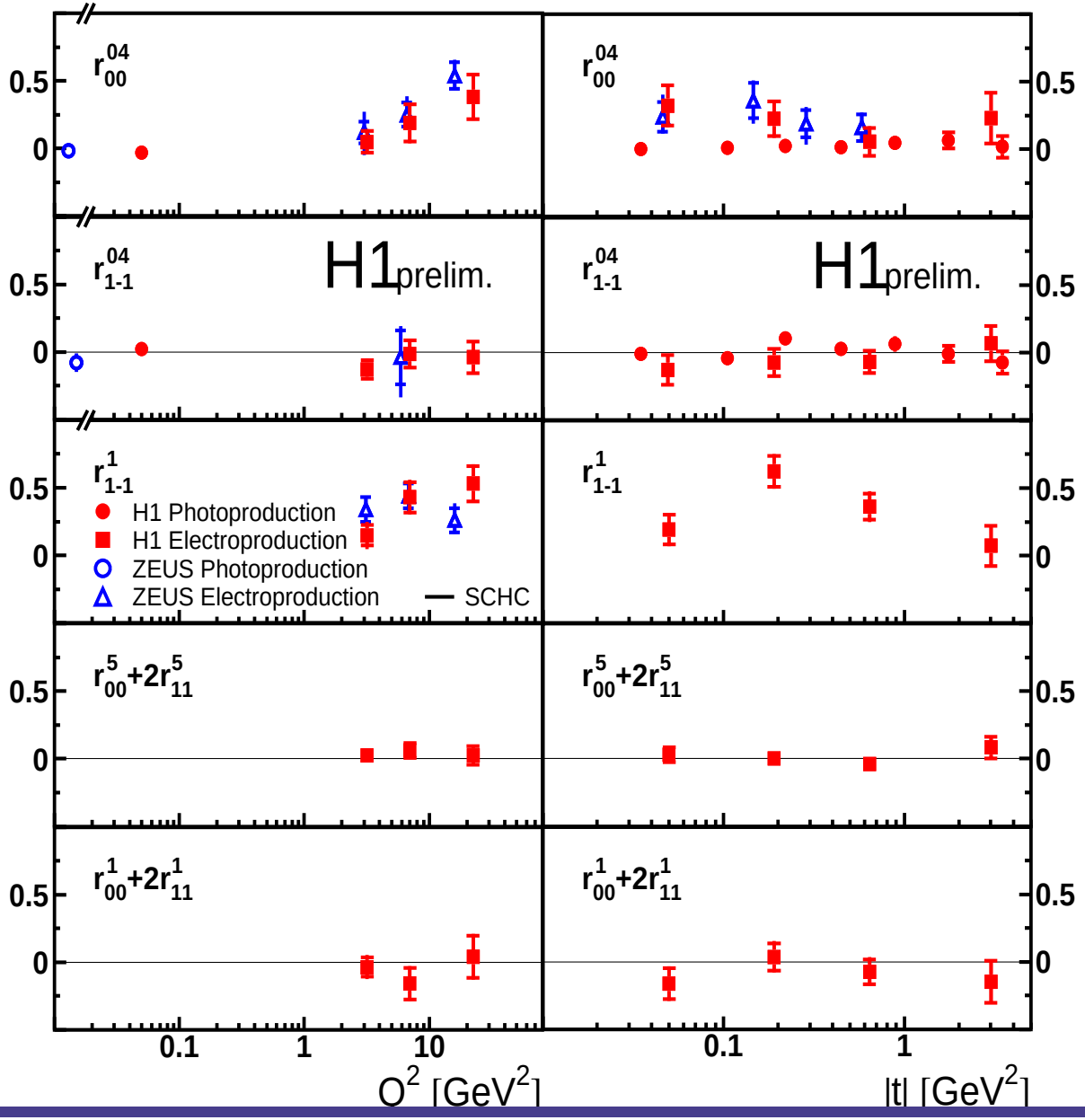
  $\Rightarrow r^{ij}_{kl} \propto T_{\lambda_V M \lambda_\gamma} T_{\lambda'_V M \lambda'_\gamma}$

No helicity flip:	T_{00} / T_{11}
Single flip:	T_{01} / T_{10}
Double flip:	T_{1-1}

- s-channel helicity conservation (SCHC)

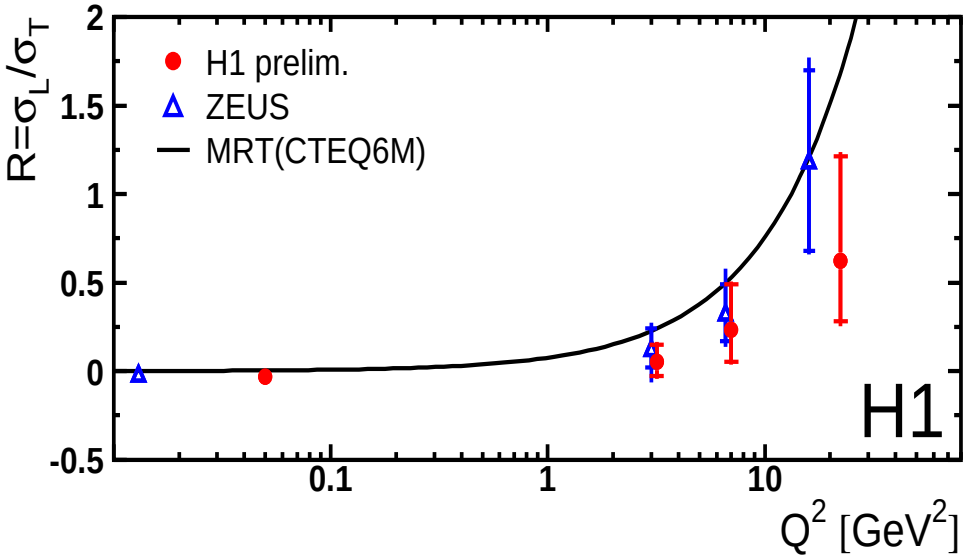
  $\Rightarrow$ Vector meson retains photon helicity

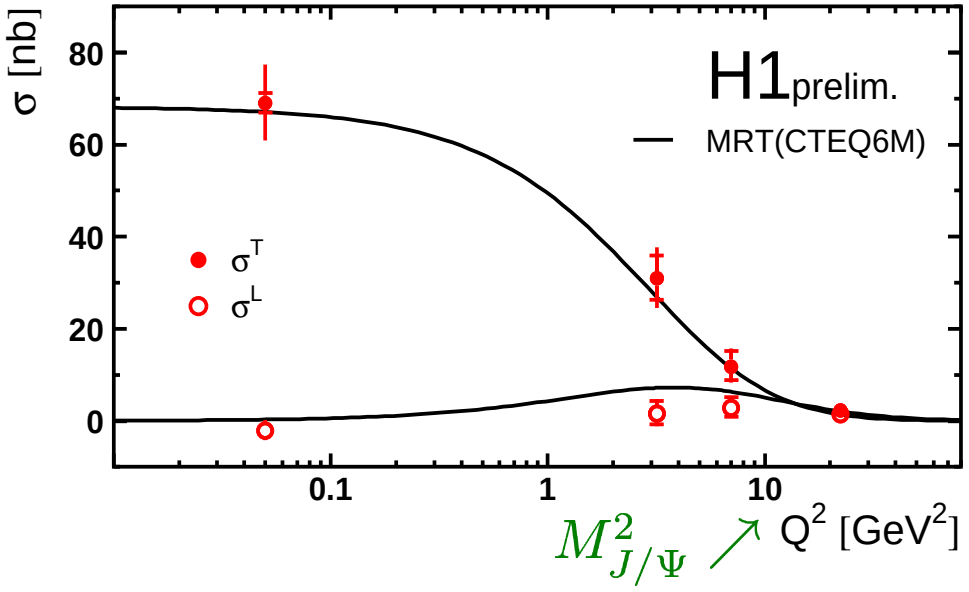
Elastic J/Ψ: Spin Density Matrix Elements



- $r_{00}^{04} > 0$ for electroproduction
  $\Rightarrow$ photon develops longitudinal component with increasing Q^2
- SCHC + Natural Parity Exchange
  $\Rightarrow r_{1-1}^{1} = \frac{1-r_{00}^{04}}{2} \approx 0.5$
  which seems to approx. hold
- Both combinations of elements $r_{00}^{5} + 2r_{11}^{5}$ and $r_{00}^{1} + 2r_{11}^{1}$ are consistent with zero $\Rightarrow$ SCHC
- Deviation from zero seen for $r_{00}^{5} + 2r_{11}^{5}$ and $r_{00}^{1} + 2r_{11}^{1}$ in ρ electroproduction analysis

Elastic J/Ψ: Longitudinal and Transverse Cross Sections





- Longitudinal to transverse cross section ratio:

$$R = \frac{\sigma_L}{\sigma_T} = \frac{r_{00}^{04}}{\epsilon(1-r_{00}^{04})}$$

where ϵ is given by:

$$\epsilon = \frac{1-y}{1-y+y^2/2}$$

and is is very close to 1 over full range

- Total cross section is given by:

$$\sigma = \sigma_T + \epsilon\sigma_L$$

$\Rightarrow$ Can extract σ_L and σ_T simultaneously

- MRT model provides reasonable description of data

ρ at High $|t|$

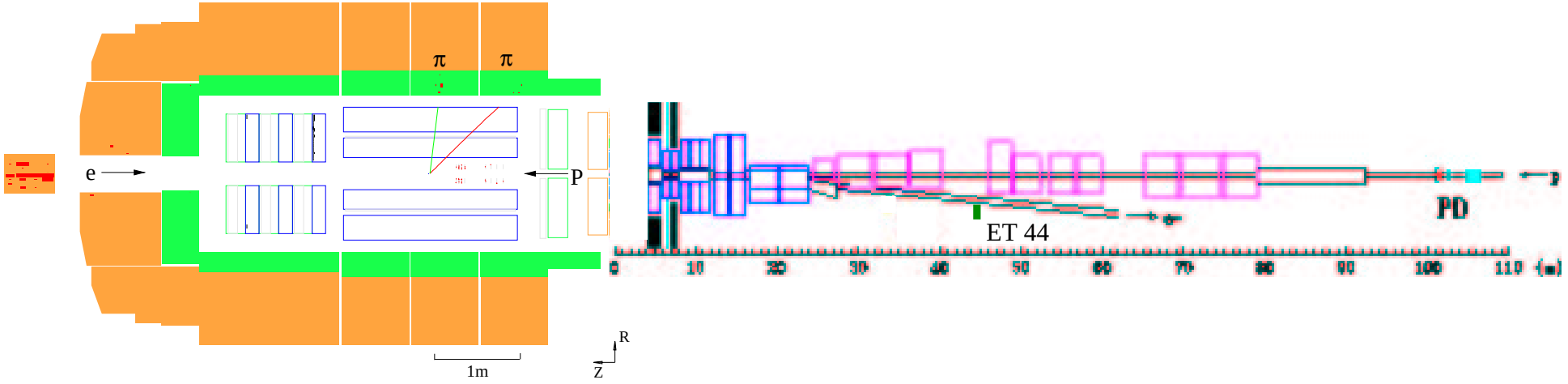
$\gamma + p \to \rho^0 + Y$ with $\rho^0 \to \pi^+\pi^-$ in tagged photoproduction

Selection:

- 2000 data period $\Rightarrow \mathcal{L} = 20.1\ \mathrm{pb}^{-1}$
- Two tracks within CJC $(20 < \theta < 155^\circ)$
- No additional neutral clusters in LAr
- Electron with $E > 15\ \mathrm{GeV}$ in 44 m tagger

Kinematics:

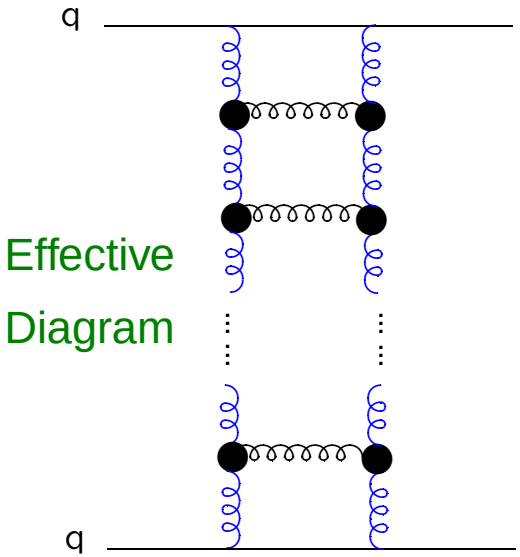
- Photoproduction $Q^2 < 0.01\ \mathrm{GeV}^2$
- Tagged electron $75 < W < 95\ \mathrm{GeV}$
- $|t|$ range $1.5 < |t\,| < 10.0\ \mathrm{GeV}^2$
- Proton remnant mass $M_Y < 5\ \mathrm{GeV}$



BFKL Model

BFKL LL:

- Sums terms in $\alpha_s^n \log^n(1/x) \Rightarrow$ Effective gluon ladder ("pomeron")



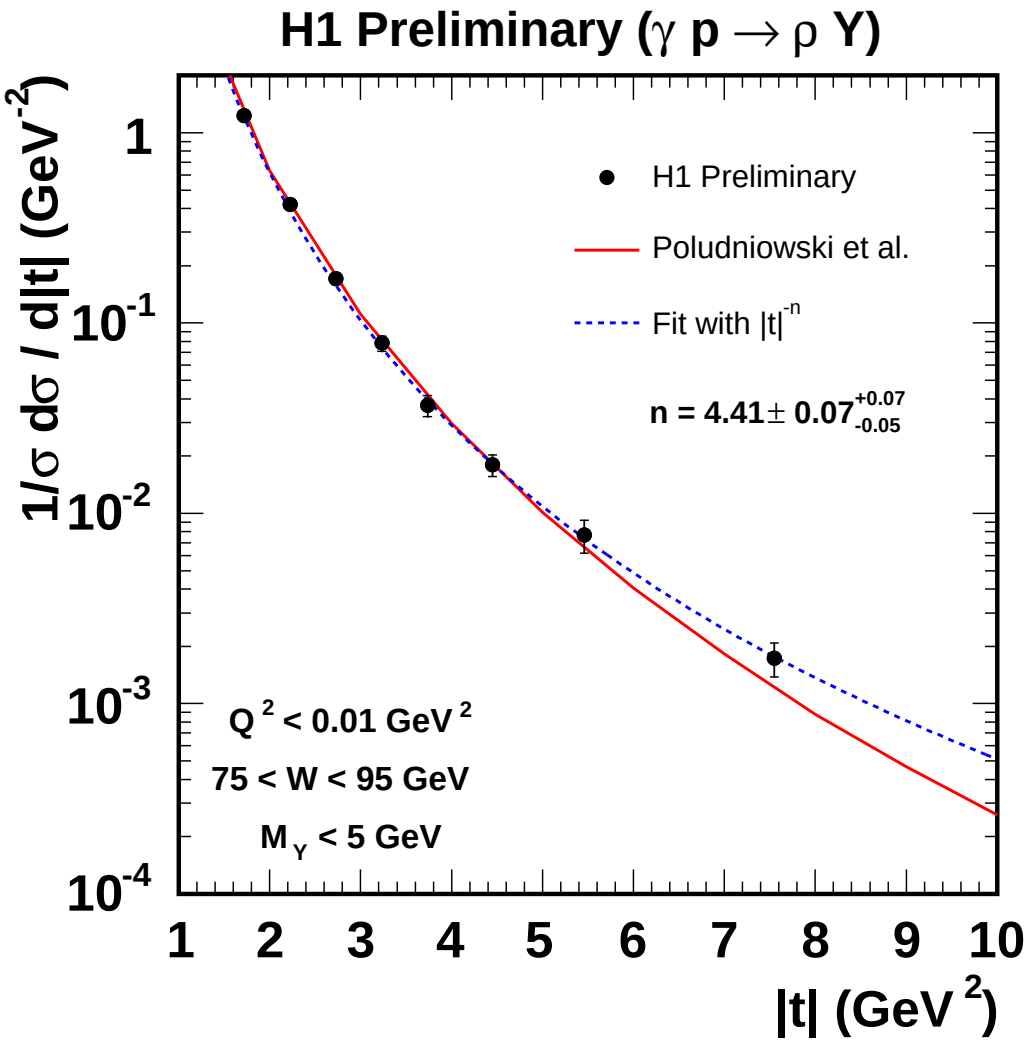
- "Random walk" with no transverse momentum k_T ordering but strong longitudinal momentum ordering $\Rightarrow$ x increases up ladder

Poludinowski *et al.*[†]:

- Challenge is to provide a simultaneous description of both the $|t|$ spectra and the SDMEs
- LL BFKL with meson production factorised from hard sub-process using a set of light-cone vector meson wavefunctions [up to twist-3]
- Free parameters:
  - α_s^{IF}: coupling of the two gluons to each impact factor
  - α_s^{BFKL}: the gluon couplings inside the gluon ladder
  - $\Lambda^2 = m_v^2 - \gamma t$: undefined energy scale
- Naively expect light quark mesons to be predominantly longitudinal $\Rightarrow$ use constituent q mass $m = m_V/2$ to introduce large chiral odd contribution and so enhance production of transverse mesons

[†] [1] R. Enberg *et al.*, JHEP **0309** (2003) 008 [hep-ph/0306232] [2] G. G. Poludniowski *et al.*, JHEP **0312** (2003) 002 [hep-ph/0311017]

High $|t|$ ρ: Dependence on $|t|$



$$n_{ZEUS} = 3.21 \pm 0.04\,(\text{stat.}) \pm 0.15(\text{syst.})$$

Fit:

- Power-like behaviour is expected at large $|t| \Rightarrow$ Data fitted with $|t|^{-n}$

$$n = 4.41 \pm 0.06\,(\text{stat.})^{+0.07}_{-0.05}(\text{syst.})$$

BFKL Model:

- BFKL model well describes data using

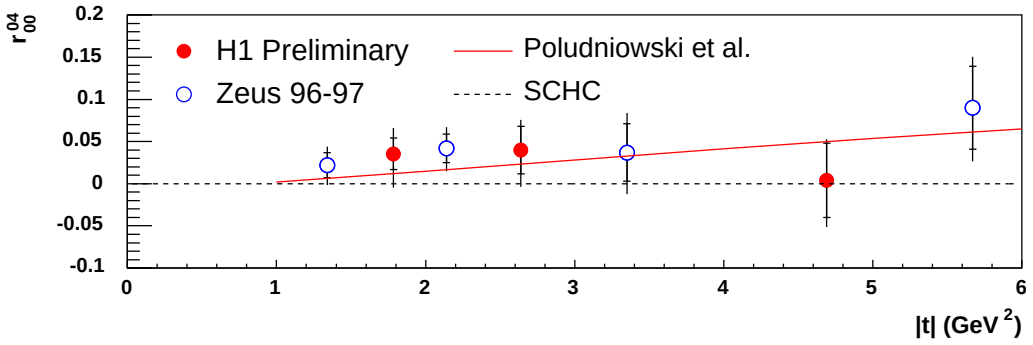
$$\alpha_s^{IF} = 0.17$$
$$\alpha_s^{BFKL} = 0.25$$
$$\gamma = 1$$

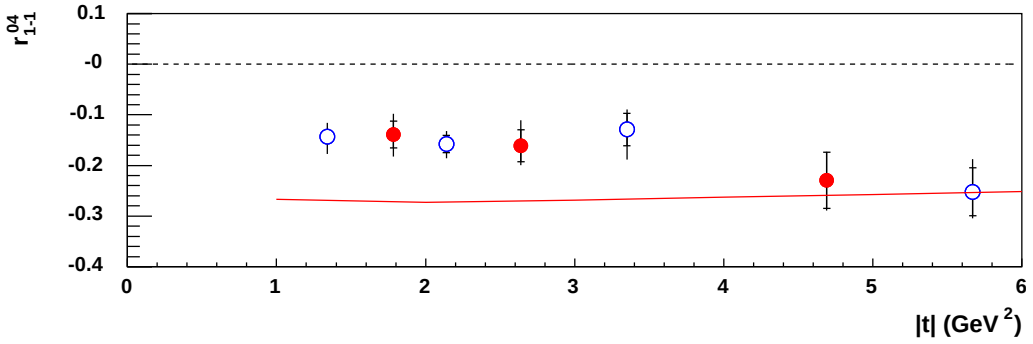
at $\langle W \rangle = 87\,\text{GeV}$ and $Q^2 = 0\,\text{GeV}^2$

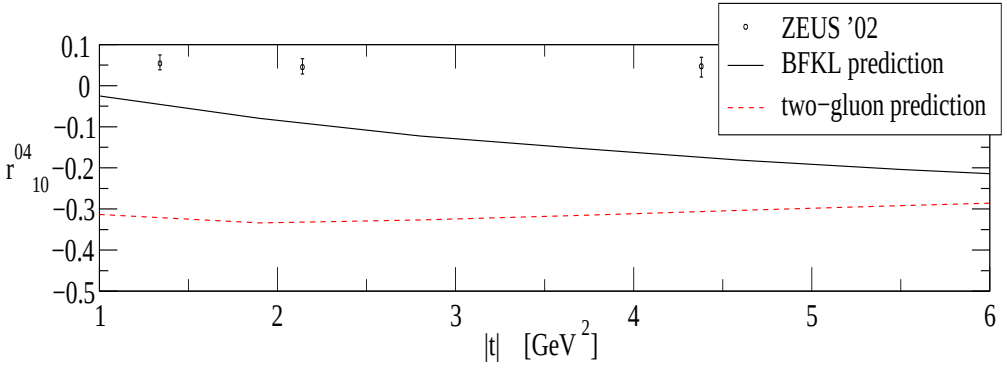
- t slope quite sensitive to the M_Y cut. Here evaluated for $M_Y < 5\,\text{GeV} \Rightarrow$ theory predicts steeper dependence than for ZEUS, where $M_Y < 25\,\text{GeV}$

High $|t|$ ρ: Dependence of SDMEs on $|t|$

H1 Preliminary (γ p $\rightarrow$ ρ Y)



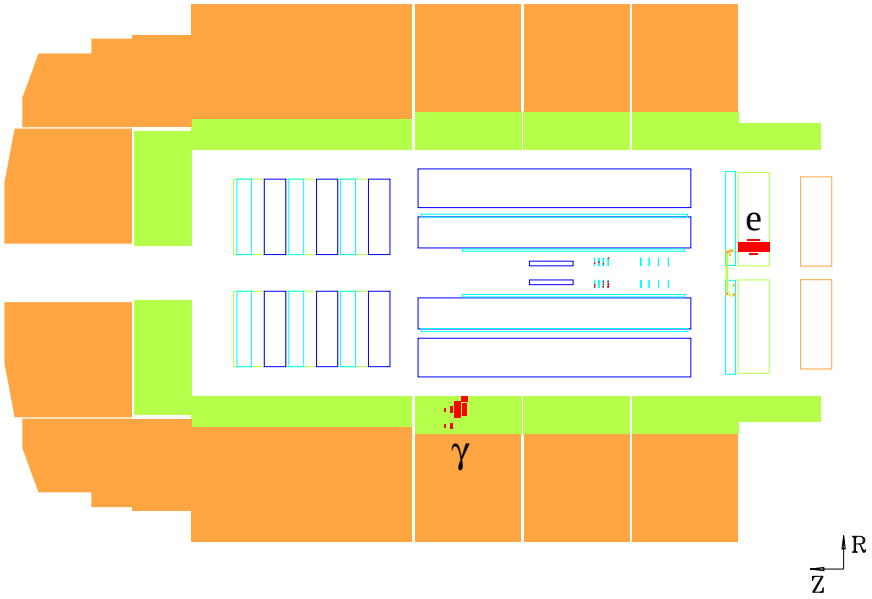




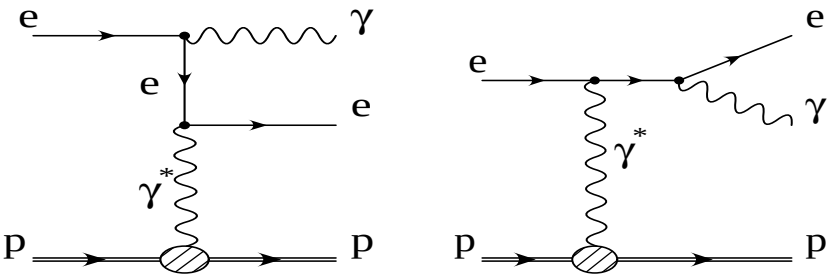
- Helicity single flip amplitude consistent with zero $\Rightarrow$ production dominated by transversely polarised ρ mesons
- Small r^{04}_{00} well described by model
- Non-zero helicity double flip amplitude $\Rightarrow$ confirmation of s-channel helicity non-conservation in ρ mesons
- Large r^{04}_{1-1} qualitatively agrees with model but prediction too big at lower $|t|$
- ZEUS r^{04}_{10} data differs significantly from zero $\Rightarrow$ production of longitudinal ρ meson (+) from transverse γ (0)
- BFKL model unable to describe r^{04}_{10} as prediction is too large and negative

Deeply Virtual Compton Scattering (DVCS)

hep-ex/0505061



- $e^+p \to e^+\gamma p$ with $\mathcal{L} = 46.5\,\mathrm{pb}^{-1}$ over 96-00
- Reaction is an interference between strong DVCS and calculable e.m. Bethe-Heitler (BH):



Selection:

- Scattered electron with $E_e > 15\,\mathrm{GeV}$ detected in SpaCal $(153 < \theta_e < 175°)$
- Photon with $P_t^\gamma > 1\ (1.5)\,\mathrm{GeV}$ for 99/00 (96/97) in LAr $(25 < \theta_\gamma < 145°)$

Kinematics:

- $Q^2 < 80\,\mathrm{GeV}^2$, $30 < W < 140\,\mathrm{GeV}$ (to enhance DVCS/BH) & $|t| < 1\,\mathrm{GeV}^2$

- DVCS cross section obtained by subtracting BH as interference cancels when integrate over azimuthal angle (between e & γ planes):

$$\frac{d^3\sigma[ep\to e\gamma p]}{dydQ^2dt}\left(Q^2,y,t\right) = \Gamma\frac{d\sigma\left[\gamma^* p\to\gamma p\right]}{dt}\left(Q^2,y,t\right)$$

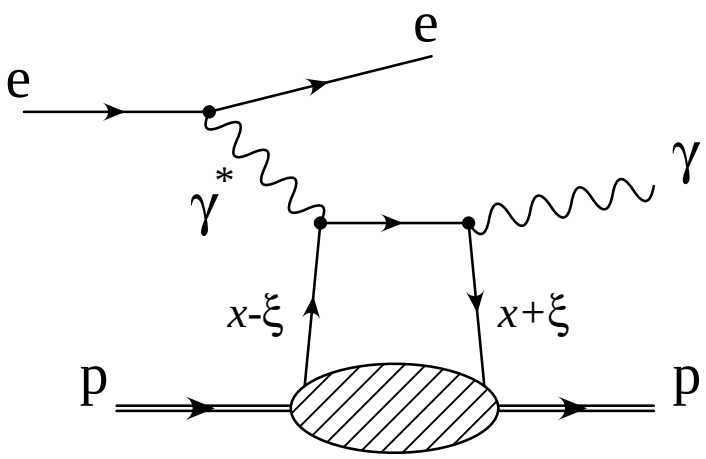
where $\Gamma\left(Q^2,y\right)$ is the transverse photon flux:

$$\Gamma = \frac{\alpha\left(1-y+y^2/2\right)}{\pi y Q^2}$$

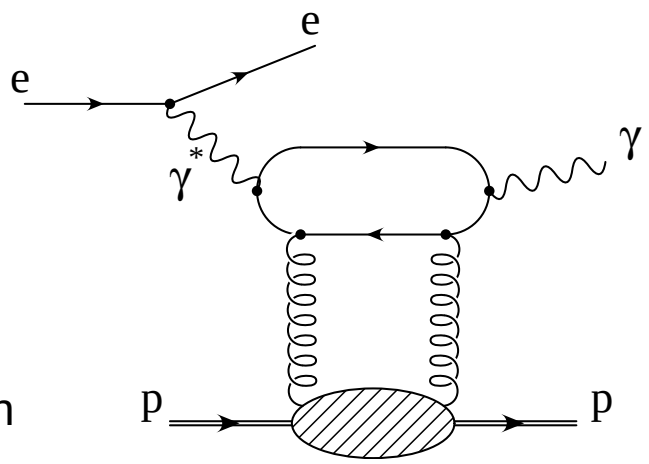
DVCS and Generalised Parton Distributions (GPDs)

- Factorisation $\Rightarrow$ pQCD calculable hard process + non-pert. proton structure effects (GPDs)

LO:



NLO E.G.:



Strong Interaction

- Clean experimental signature + not hampered by wavefunction uncertainties as with VMs
- Skewdness ξ: measure of momentum difference between emitted & absorbed partons

  [caused by the necessary transition from a virtual photon to a real one]

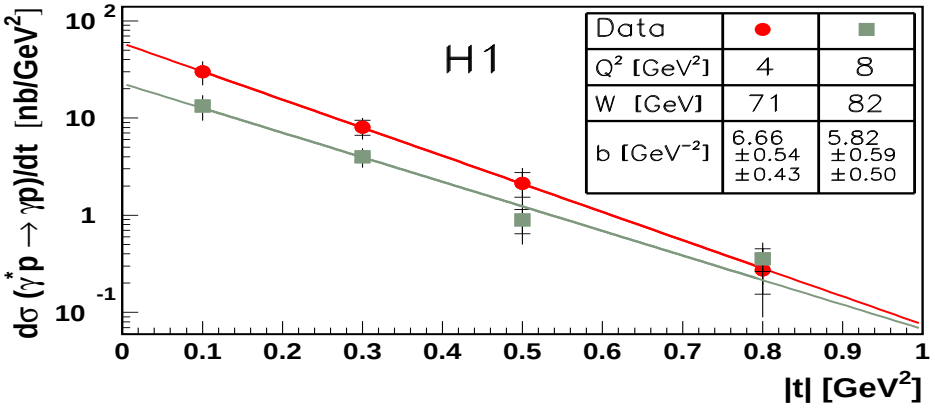
- GPDs: correlations between partons in proton & transverse momentum (not in PDFs)

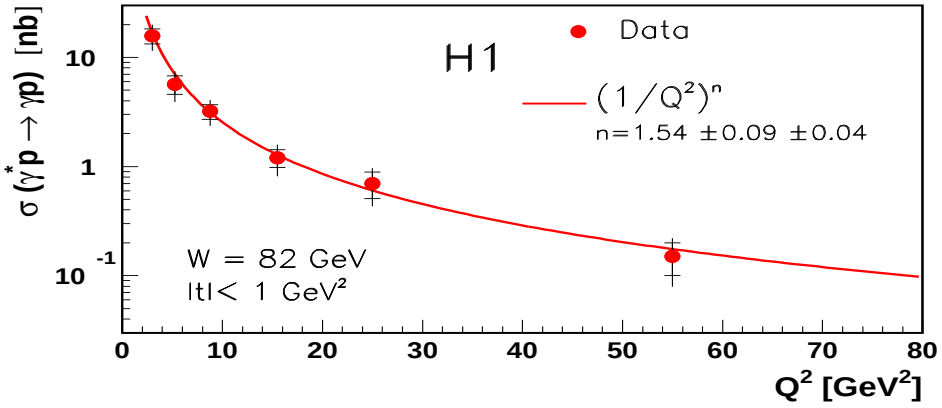
  $E^{q,g}(x,\xi,t) \Rightarrow$ has no analogue in ordinary PDF approach

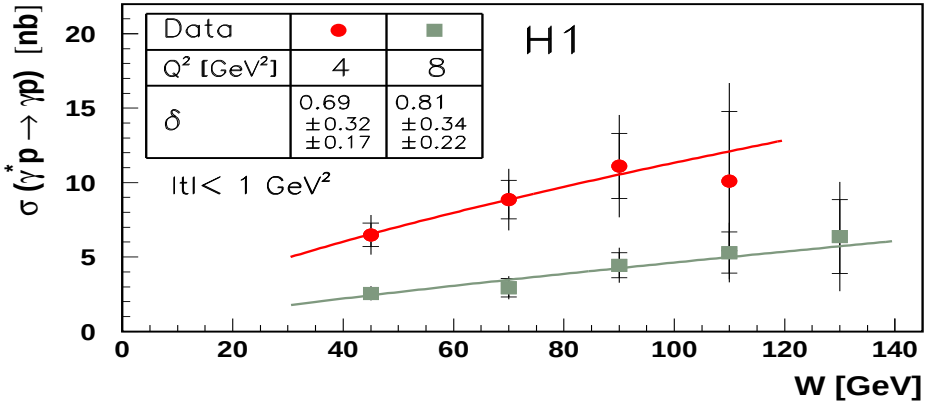
  $H^{q,g}(x,\xi,t) \Rightarrow$ reduce to ordinary PDFs [$q(x)$ & $xg(x)$] in limit $\xi \to 0$ & $t \to 0$

- At low x main contribution is provided by $H^{q,g}(x,\xi,t)$, while $E^{q,g}(x,\xi,t)$ is small

DVCS: t, Q^2 and W Dependencies







- First measurement of t dependence
- Fit with an exponential: $\frac{d\sigma}{dt} \propto e^{-bt}$
- No dependence of b on Q^2 within errors
- Average of two data sets at $Q^2 = 8\,\mathrm{GeV}^2$

  $\Rightarrow b = 6.02 \pm 0.35 \pm 0.39\,\mathrm{GeV}^{-2}$

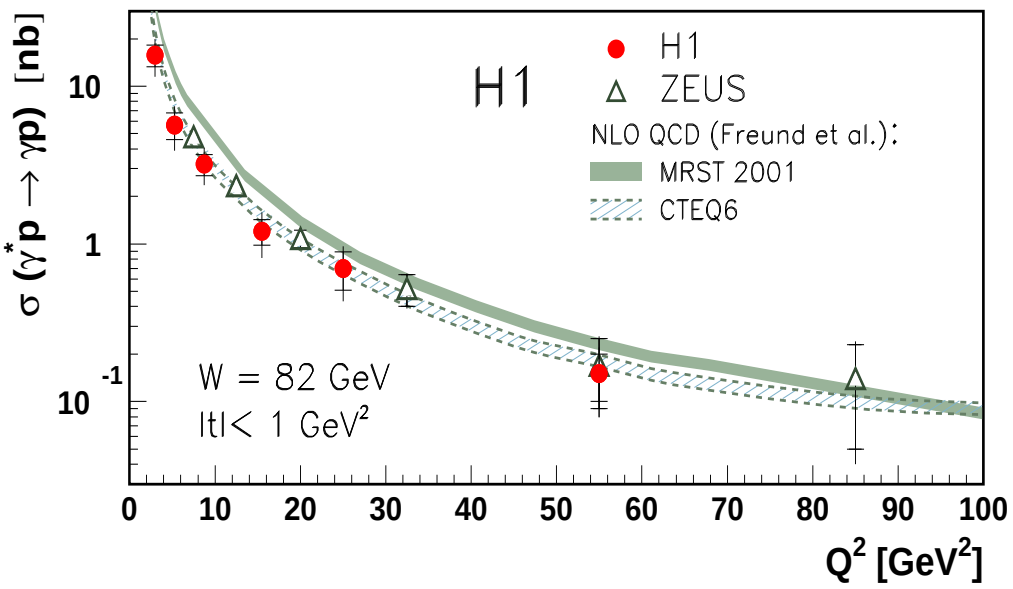
- Fit with a power law: $\sigma \propto \left(1/Q^2\right)^n$
- n consistent within different Q^2 ranges
- Average 2 sets $\Rightarrow n = 1.54 \pm 0.09 \pm 0.04$
- Shallower than for VMs (no VM wavefunction)

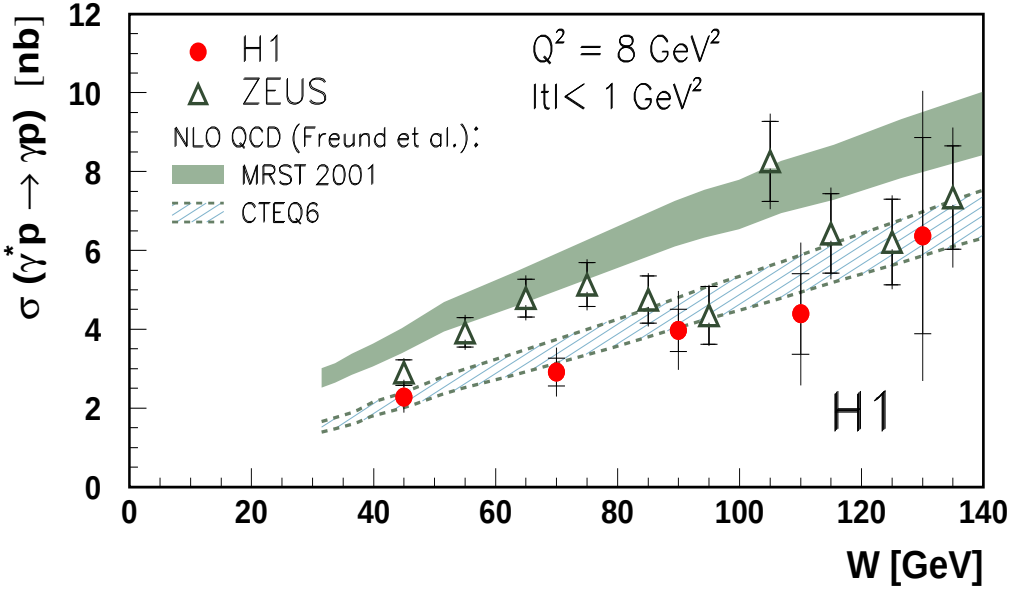
- Fit with a power law: $\sigma \propto W^{\delta}$
- No dependence of δ on Q^2 within errors
- Average of two data sets at $Q^2 = 8\,\mathrm{GeV}^2$

  $\Rightarrow \delta = 0.77 \pm 0.23 \pm 0.19$

- Very Close to $\delta_{J/\Psi}(\gamma p) \Rightarrow$ Hard Regime

DVCS: Comparison with ZEUS and NLO QCD





- Reasonable agreement with ZEUS data
  [corrected to H1 Q^2/W using ZEUS n/δ]

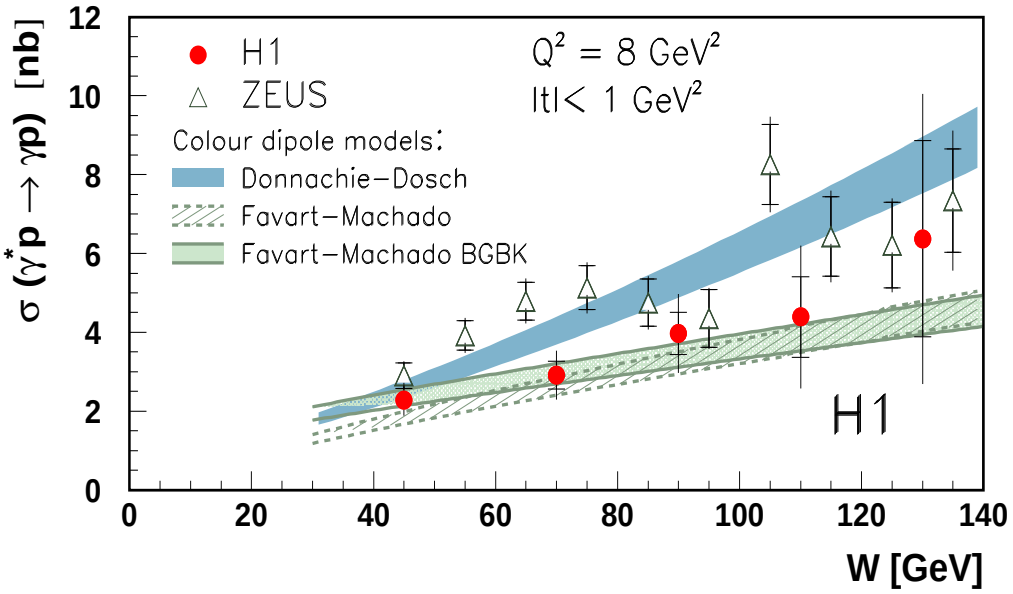
Freund & McDermott NLO QCD Model:

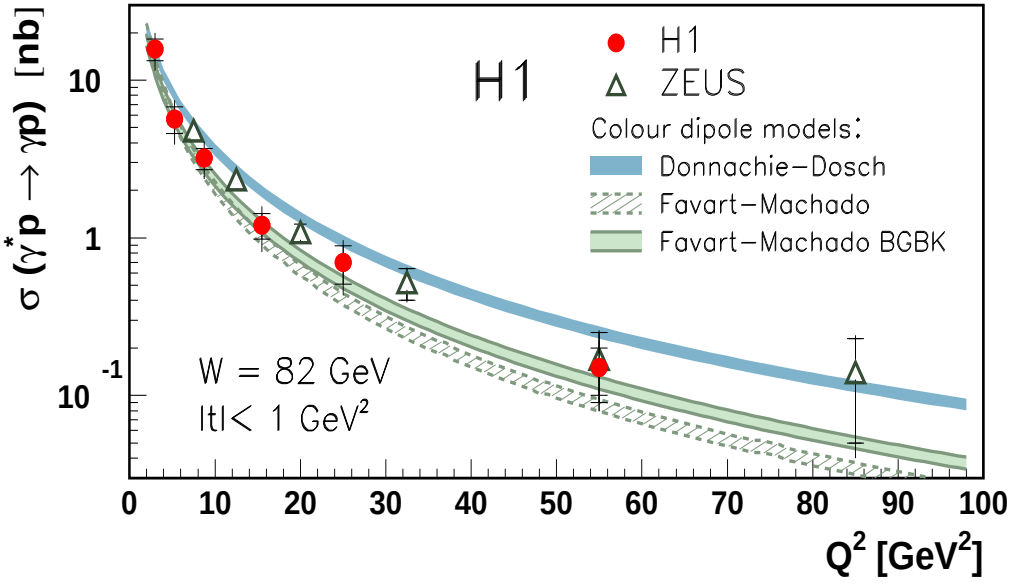
- 1st absolute prediction in diffraction!
- Normalisation uncertainty is reduced since b is extracted from data
- DGLAP Region ($|x| > \xi$) $\Rightarrow$
  Uses ordinary MRST2001/CTEQ6F PDFs
  QCD evolved from a starting scale of Q_0^2

$$H^q\left(x,\xi,t;Q_0^2\right) = q\left(x;Q_0^2\right)e^{-bt}$$

- Skewing generated purely dynamically
- ERBL Region ($|x| < \xi$) $\Rightarrow$
  Polynomial matched smoothly at $x = \xi$
- Good description of data if use CTEQ6F

DVCS: Comparison with Colour Dipole Models (CDMs)





- CDMs factorise DVCS amplitude into:
  1. Wavefunction for γ to fluctuate into $q\bar{q}$
  2. Cross section for $q\bar{q}$ interaction with p
  3. Wavefunction for outgoing photon
- Models differ in dipole σ parameterisation

  Donnachie & Dosch $\Rightarrow$ Soft and hard $I\!P$ exchange depending on dipole size

  Favart & Machado $\Rightarrow$ GBW saturation model with DGLAP evolution (BGBK)
- Good description of the data shape and normalisation + DGLAP evolution improves Favart & Machado description

Summary

Elastic J/Ψ:

- Significantly extends W range up to $W = 305\,\mathrm{GeV}$
- Good description of Q^2 & W data by MRT (with CTEQ6M)
  - May be used to constrain gluon at low x
- No violation of SCHC observed

High $|t|\rho$:

- Measurement of ρ mesons up to $t = 10\,\mathrm{GeV}^2$
- Confirms violation of SCHC
- BFKL model provides good description of t dependence and moderate description of r^{04}_{00} & r^{04}_{1-1} but cannot reproduce r^{04}_{10}

DVCS:

- Complete HERA I analysis performed
- 1st measurement of t dependence of cross section
- Good description of data by NLO QCD (& also CDMs)
  - Works even at lowest Q^2 ($\sim 2\,\mathrm{GeV}^2$)
  - Skewing generated purely dynamically

HERA II analyses are still to come